(54) Title: MONITORING

(57) Abstract

The operation of an engine (2) or other assembly is monitored by detecting the sound it makes and deriving from this, in conjunction with its speed, temperature and control settings, a multi-dimension condition vector. The vector changes during operation of the engine (2) and is supplied to a processor (4) which builds up a model of the engine (2) at different stages of operation such as by a sequence-learning neural net or by a hidden Markov model. When an atypical condition vector is received, the processor (4) generates an alert signal to a display (41).
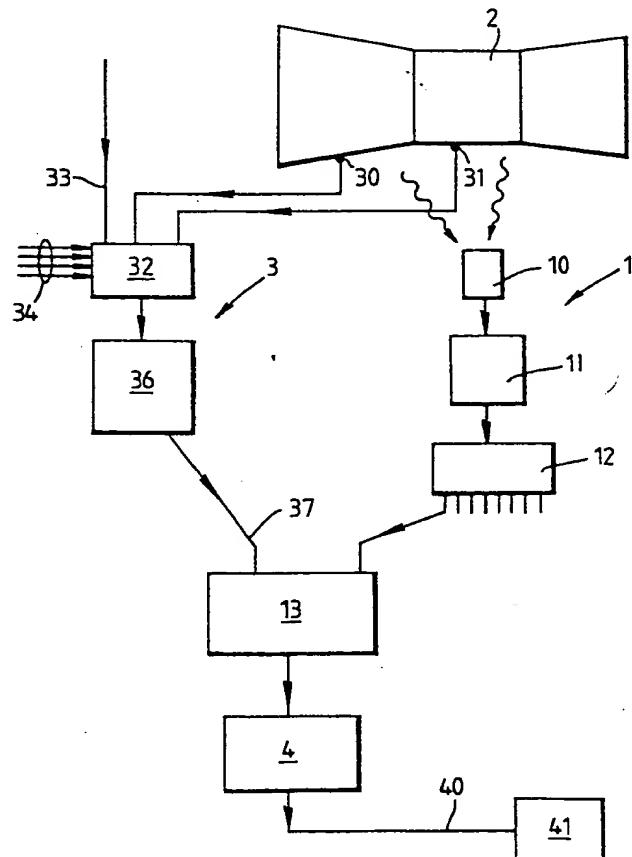
MONITORING

This invention relates to monitoring.

The invention is more particularly concerned with methods and apparatus for monitoring the condition of assemblies such as a gas-turbine engine in an aircraft.

It is known to monitor the vibration produced by engines and bearings and to detect when certain frequencies of the vibration exceed a predetermined level so as to establish when wear or damage has been produced. This can be a useful technique but is only capable of detecting significant amounts of wear or damage. This is because the vibration spectrum produced by the engine or bearing varies normally according to its operational condition such as speed, temperature, loading and so on. The amplitude above which one frequency of vibration will trigger a wear or damage signal must be sufficiently high that it is not triggered at the maximum amplitude experienced in normal use. This makes the apparatus relatively insensitive to incipient damage. Furthermore, although previous systems relying on the detection of spectral peaks can be used to identify known faults which cause spectral peaks at predictable frequencies, they are not capable of responding to more subtle spectral variations, such as distortion not involving sharp peaks,

or unusual combinations of peaks, or unusual sequences. The response of previous systems is therefore severely limited as far as incipient or hitherto unknown fault conditions are concerned.

It is an object of the present invention to provide monitoring methods of improved sensitivity.

According to the present invention there is provided a method of monitoring the condition of an assembly including the steps of deriving signals representative of the condition of the assembly, continuously building a model of the assembly at different stages of use through the life of the assembly such that the model is modified by any ageing of the assembly, and detecting the amount of deviation of the condition of the assembly from the model of the assembly.

Where the method is used to monitor the condition of a sound-generating assembly, the step of deriving signals representative of the condition of the assembly includes monitoring the acoustic spectrum of the assembly such that the model includes information about the acoustic spectrum of the assembly at different stages of use through the life of the assembly. The acoustic spectrum is preferably the acoustic spectrum transmitted through air, and the acoustic spectrum is monitored with a

microphone.

The assembly may be an engine such as a gas-turbine engine. The step of deriving signals representative of the condition of the assembly may include monitoring the speed of the engine.

A multi-dimension vector may be established in respect of the condition of the assembly. The model of the assembly may be built using a sequence-learning neural net or a hidden Markov model.

A model may be built of a first assembly, this model being utilized on a second assembly of the same kind as the first assembly, and the model being modified by operation of the second assembly.

An engine monitoring apparatus and method, in accordance with the present invention, will now be described, by way of example with reference to the accompanying drawings, in which:

Figure 1   shows the apparatus schematically; and

Figures 2   are graphs illustrating the change in
and 3   acoustic spectrum.

The monitoring apparatus comprises a first acoustic
channel 1 responsive to the sound generated by the
gas-turbine engine 2 and a second channel 3 responsive to
the operational condition of the engine. The two channels
1 and 3 together produce a condition vector output which
is compared in a processor 4 with a model of the engine
built up from previous operation of that engine.

The acoustic channel 1 includes a microphone 10
which is responsive to the airborne sound generated by the
engine 2 in operation. The microphone 10 is not
necessarily responsive to sound within the range of human
hearing but typically will have a frequency response
beyond about 100KHz. The electrical output from the
microphone 10 is supplied to a digitising unit 11 which
supplies a digitised output to a spectrum analyser 12 of
conventional construction which produces time-averaged
signals for each of several different bands. Typically
the spectrum analyser 12 produces 64 parallel outputs at
different freqencies each with a width of 1 KHz and with
time averaging over 0.2 seconds. The outputs from the
analyser 12 are supplied to a processing unit 13 which
also receives a second input from the second channel 3.

The second channel 3 includes an engine spool speed

sensor 30 and a exhaust gas temperature sensor 31 which

supply output signals in response to these operational

conditions of the engine 2 to an analogue-to-digital

converter 32. The converter 32 also receives inputs on

line 33 representative of the throttle or other engine

control settings which indicate the desired thrust of the

engine. The throttle and any other active, that is,

pilot-imposed, control are the most important non-acoustic

parameters because the apparatus will learn to associate

certain response sequences with imposed control sequences

and so build up its own internal sequence monitor,

signalling when an unexpected sequence occurs. Signals

representing aircraft performance, such as its attitude,

airspeed or the like are supplied on lines 34 to the

converter 32. Various other flight data could be supplied

to the converter 32. The output of the converter 32 is

supplied to a processor 36 which produces a

multi-dimensional vector signal representative of the

stage of operation of the engine 2. This vector signal is

supplied via line 37 as the second input of the processing

unit 13. The processing unit 13 produces a combined

N-dimensional engine condition vector from the two inputs

and supplies this to one input of the processor 4.

The processor 4 preferably operates through self-learning techniques, such as involving a sequence-learning, time-aware, neural net of the multi-layer perceptron variety or a hidden Markov model similar to that used in speech recognition.

The first time that the engine is operated in flight, the processor 4 builds up a model of the engine's operation during all stages of that flight from the engine condition vector. Repeated operation of the engine modifies this model to build up an average or typical model of the engine's operation. The system gradually becomes familiar with the engine's acoustic behaviour in the engine's own environment and during the engine's day-to-day operation. The model will be modified as the engine ages. Sounds caused by interaction between the engine and airframe form a part of this acoustic model and do not need to be identified or filtered out.

When an atypical engine condition vector is received by the processor 4, this causes the processor to generate an alert signal which is supplied via line 40 to a display 41 or other utilisation device such as a recorder or engine control unit. The alert signal preferably indicates the degree of departure of the engine condition vector from the model, such as in the form of a probability that the condition vector is a realization of

the statistically typical behaviour. If the model takes
the form of a sequence-recognizing neural network, the
network will act as a `novelty filter´ and indicate an
unknown input sequence. If the model is a Markov model, a
potential fault condition will be assigned an increasing
severity level as the actual sequence becomes a lower
probability realization of the Markov representation. The
information is used to alert ground maintenance staff of
deviations from normal operation which should be
investigated, or to alert the pilot of more serious
emergencies. This system does not, therefore, just
trigger an alarm on exceeding a threshold but raises
signals of varying degrees of urgency from mild disquiet
to major emergency according to whether its input is a
minor deviation or a gross deviation from what it has come
to understand as normal. A minor deviation would
accummulate into a major one if it were persistant but
would be forgotton if it were momentary. The nature of
the deviation is self learned by the system and is not
programmed by humans. In addition to discerning
commonality within and between the states of the engine,
because the apparatus is time-aware, it is able to
familiarize itself with the sequences in which state
transitions occur in the engine or other assembly.

In some cases it may be preferred to store a model
of the engine's operation derived from operation of a
different but same type of engine at the start of
operation of the monitoring system. Alternatively, the
system could start without any model, and a preliminary
model be established on the first occassion that the
engine is operated. It will be appreciated that during
the earliest flights, the reporting of unusual conditions
will be unreliable but will become increasingly discerning
and useful after several flights when it will have
accumulated knowledge in the form of a set of neural
network synaptic strengths and biasses or a Markov model
in a manner analogous to that of a speech recognizer.

Prior to operation, it is necessary to monitor the
acoustic spectrum produced by the engine, or by a
different engine of the same type, in normal operation and
at different stages of operation. By repeating this
procedure in different conditions, a statistical
representation of the normal operational behaviour of the
engine is established. Various techniques used in pattern
recognition and speech recognition could be used to build
up a model of the acoustic spectrum of the engine at
different stages of operation, such as by Markov modelling
or neural networks.

With reference to Figure 2 there is shown a highly
simplified representation of the way in which the
amplitude of acoustic energy at two different frequencies
1KHz and 5KHz varies with engine speed in revolutions per
minute. The locus A to B represents the stage of taxiing
along a runaway to maximum rpm at take-off at the point
B. The point C indicates the aircraft cruise condition
for most of the flight. The store 5 contains a model of
this but in a more complex form with a greater number of
frequencies and other engine functions in addition to
engine speed.

While the aircraft follows the locus A to D to
within a predetermined range, the input to the comparator
4 will be closely similar to the stored model and no
output indicating departure from the model will be
produced.

With reference now to Figure 3, there is
illustrated an irregular and an abnormal engine
performance. The point C´ represents an unusual cruise
state on an unusual trajectory through the normal states
and this would cause the comparator 4 to produce an alert
signal on line 40 to the display 41. The point C"
represents a very abnormal state on an abnormal
trajectory and would cause the comparator 4 to produce an
urgent alarm signal on line 40 to the display 41.

The monitor apparatus of the present invention can be very sensitive because it will respond to acoustic spectra of the engine which may be unusual at, for example, low speed but may be within the normal spectrum at high speed. In this way it may be possible to detect incipient damage to the engine before failure occurs. In its simplest embodiment the apparatus only gives an indication that there is some departure from normal operation. The apparatus could, however, have diagnostic capabilities. A database of unusual deviations could be matched with known faults after some operational experience. This would become more detailed as greater operational experience is built up, the apparatus gradually being able to identify a greater number of specific likely faults. Instead of detecting airborne sound, the invention can be used with acoustic energy including vibration transmitted through solid structures.

If the apparatus has learned the environment and individual characteristics of one engine and is then transferred to another engine of the same type this could result in non-fault deviations from the learned behaviour patterns which would be signalled to the maintenance engineers. Similarly, if the engine is serviced or repaired, or if there is a change in microphone position or the like, this could produce deviations from the model.

Subsequent operation of the engine will cause the apparatus to acclimatize soon to the new characteristics which will be seen as normal. The signalling of temporary deviations to maintenance engineers could be a useful part of building up a diagnostic database. Longer term changes will be assimilated into the model as they happen and will not lead to any signalling of departure from normal operation. Major or abrupt deviations will not occur often enough to be accepted as normal and always signal an alert at a suitable level.

The invention is not confined to use with engines but could be used with other sound-generating equipment such as bearings, machine tools, automated assembly equipment and production lines.

The invention could also have application with other assemblies, involving any complex massively parallel data which need not be acoustic. For example, a number of thermal sensors could be placed around an engine and a self-organising neural net detecting trends in their combined readings could be used to signal unusual behaviour. Alternatively, strain gauges around an airframe, or similar assembly, could be subject to initial analysis by self-organising neural networks with possible early warning of excessive structural stress. The strain gauge could be provided by optical fibres embedded in

composite material in such a way that strain causes

attenuation or reflection of radiation passing along the

fibre, at the location of the strain. These front-end

neural nets could pass their findings to a central

processor with sufficient intelligence to signal

irregularities in any aspect of the monitored assembly.

CLAIMS

1.   A method of monitoring the condition of an
assembly (2) including the steps of deriving
signals representative of the condition of the
assembly, continuously building a model of the
assembly at different stages of use through the
life of the assembly such that the model is
modified by any ageing of the assembly, and
detecting the amount of deviation of the condition
of the assembly from the model of the assembly.

2.   A method of monitoring the condition of a
sound-generating assembly according to Claim 1,
characterised in that the step of deriving signals
representative of the condition of the assembly
(2) includes monitoring the acoustic spectrum of
the assembly such that the model includes
information about the acoustic spectrum of the
assembly at different stages of use through the
life of the assembly.

3.   A method according to Claim 2, characterised in
that the acoustic spectrum is the acoustic
spectrum transmitted through air, and that the
acoustic spectrum is monitored with a microphone
(10).

4.   A method according to any one of the preceding

        claims, characterised in that the assembly is an

        engine (2).

5.   A method according to Claim 4, characterised in

        that the engine is a gas-turbine engine (2).

6.   A method according to Claim 4 or 5, characterised

        in that the step of deriving signals

        representative of the condition of the assembly

        includes monitoring the speed of the engine (2).

7.   A method according to any one of the preceding

        claims, characterised in that a multi-dimension

        vector is established in respect of the condition

        of the assembly.

8.   A method according to any one of the preceding

        claims, characterised in that the model of the

        assembly is built using a sequence-learning neural

        net.

9.   A method according to any one of Claims 1 to 7,

        characterised in that the model of the assembly is

   built using a hidden Markov model.

- 15 -

10.   A method according to any one of the preceding
        claims, characterised in that a model is built of
        a first assembly, that this model is utilized on
        a second assembly of the same kind as the first
        assembly, and that the model is modified by
        operation of the second assembly.
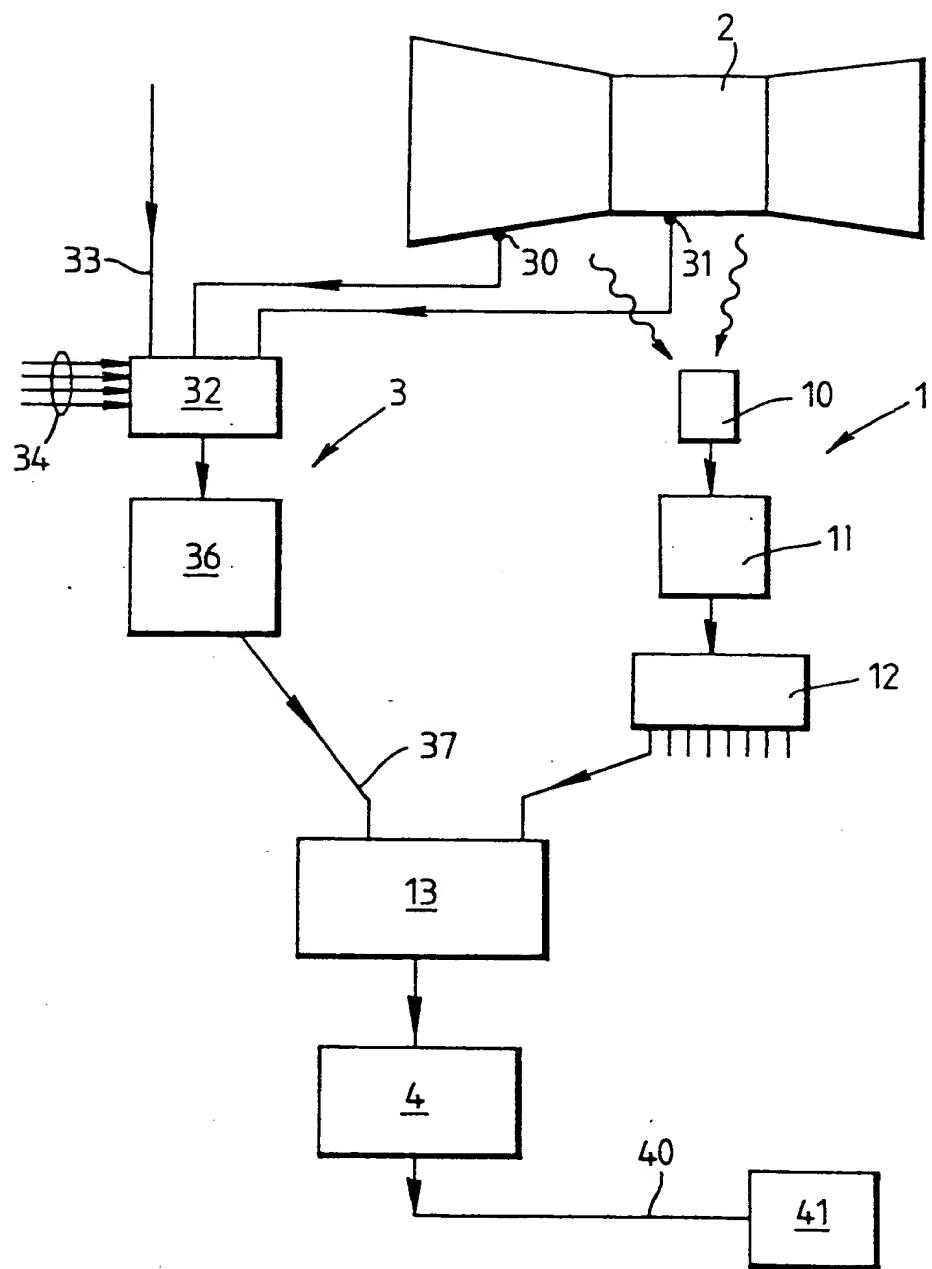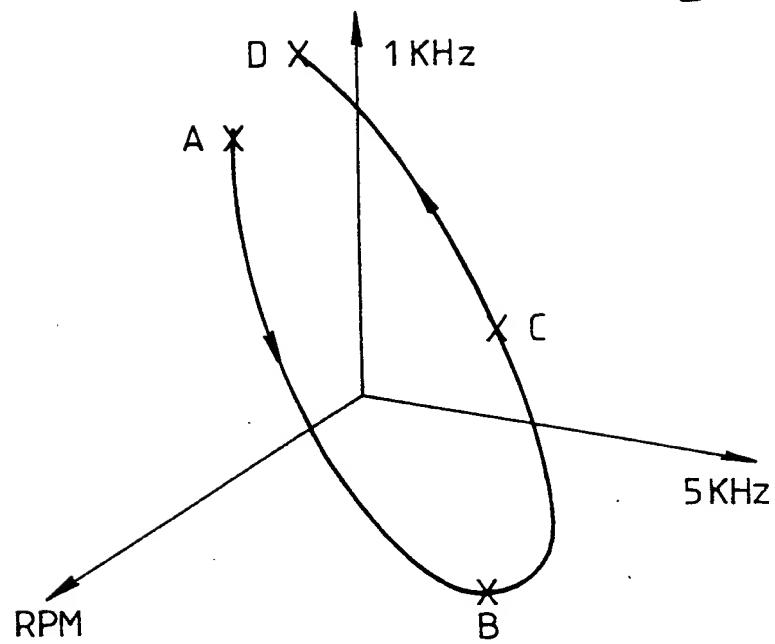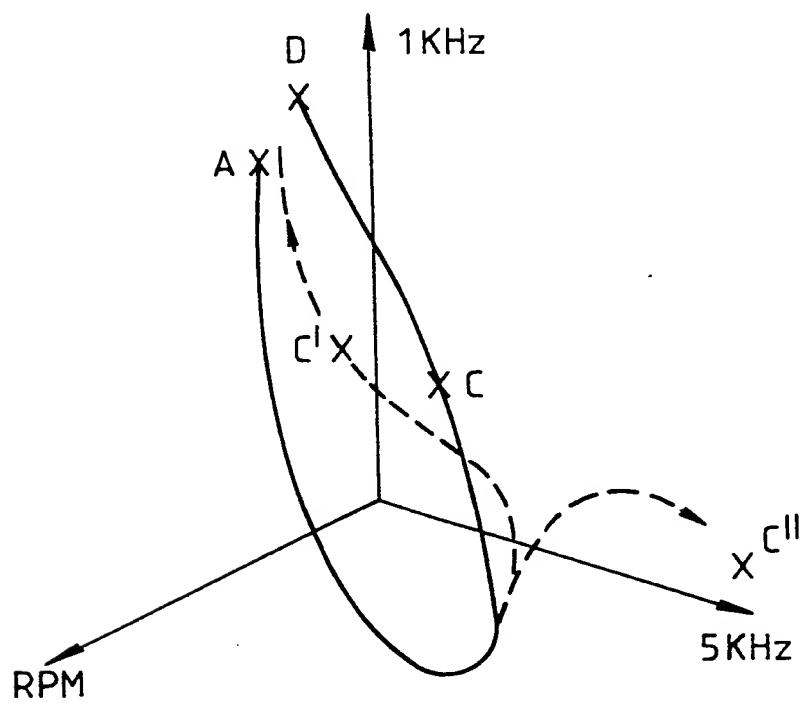
Fig. 1.

2/2

Fig. 2.

Fig. 3.

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

Int.Cl. 5   G07C3/00 ;   G06F15/74

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl. 5	G07C ; G06F ; G01H ; F01D

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category[°]	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	US,A,4215412 (BERNIER) 29 July 1980 see abstract; claims 1-16; figures see column 3, line 8 - column 8, line 28	1, 4-7
Y		8, 9
A		10

X	EP,A,0002232 (IRD MECHANALYSIS) 13 June 1979 see page 1, line 19 - page 3, line 1; claims 1-21; figures	1, 2, 4
Y		3
A		7

Y	DE,A,3332941 (KLETEK) 28 March 1985 see page 10, line 22 - page 11, line 11; figures	3
A		1, 2

Y	WO,A,8810474 (UNIVERSITY OF WEST VIRGINIA) 29 December 1988 see page 2, line 20 - page 5, line 16; figure 1	8

	-/--	

° Special categories of cited documents :[10]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
03 MAY 1990	14. 06. 90

International Searching Authority	Signature of Authorized Officer
EUROPEAN PATENT OFFICE	MEYL D.

Category °	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No.
Y	US,A,4783804 (AMTT) 08 November 1988 see abstract; figures	9
A		1, 10
A	--- US,A,4336595 (ADAMS) 22 June 1982 see abstract; figures	1
A	--- EP,A,0023879 (UNITED TECHNOLOGIES) 11 February 1981	
A	--- EP,A,0085570 (BECTON) 30 May 1984 ---	

III. DOCUMENTS CONSIDERED TO BE RELEVANT   (CONTINUED FROM THE SECOND SHEET)

ANNEX TO THE INTERNATIONAL SEARCH REPORT
ON INTERNATIONAL PATENT APPLICATION NO.

PCT/GB 90/00076
SA   33886

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.   04/05/90

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US-A-4215412	29-07-80	None		
EP-A-0002232	13-06-79	US-A-	4184205	15-01-80
		CA-A-	1139881	18-01-83
		JP-A-	54094061	25-07-79
		US-E-	RE31750	27-11-84
DE-A-3332941	28-03-85	None		
WO-A-8810474	29-12-88	None		
US-A-4783804	08-11-88	FR-A-	2579357	26-09-86
		JP-A-	61262799	20-11-86
US-A-4336595	22-06-82	CA-A-	1165443	10-04-84
EP-A-0023879	11-02-81	US-A-	4280185	21-07-81
		CA-A-	1143063	15-03-83
		JP-A-	56029140	23-03-81
EP-A-0085570	10-08-83	US-A-	4488240	11-12-84

THIS PAGE BLANK (USPTO)